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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

# TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2003/29

# RESPIRATORY DEMAND IN INDIVIDUALS PERFORMING RIGOROUS PHYSICAL TASKS IN CHEMICAL PROTECTIVE ENSEMBLES

by

**Jonathan W. Kaufman, Ph.D.**
**Sherry A. Hastings, ARINC, Inc.**

**5 May 2003**

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**RELEASED BY**:

DP Gleisner 5 May 2003

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| REPORT DOCUMENTATION PAGE | | | | | Form Approved<br>OMB No. 0704-0188 | |
|---|---|---|---|---|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.** | | | | | | |
| 1. REPORT DATE<br>5 May 2003 | | 2. REPORT TYPE<br>Technical Report | | | 3. DATES COVERED<br>September 2002 | |
| 4. TITLE AND SUBTITLE<br><br>Respiratory Demand in Individuals Performing Rigorous Physical Tasks in Chemical Protective Ensembles | | | | | 5a. CONTRACT NUMBER<br><br>5b. GRANT NUMBER<br><br>5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S)<br><br>Jonathan W. Kaufman, Ph.D.<br>Sherri Hastings, ARINC, Inc. | | | | | 5d. PROJECT NUMBER<br><br>5e. TASK NUMBER<br><br>5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>Naval Air Warfare Center Aircraft Division<br>Bldg 2187 Suite 2280<br>48110 Shaw Road, Unit #5<br>Patuxent River, Maryland 20670-1906 | | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER<br><br>NAWCADPAX/TR-2003/29 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Marine Corps Systems Command<br>2033 Barnett Avenue<br>CSLE/NBC<br>Quantico, Virginia 22134-5010 | | | | | 10. SPONSOR/MONITOR'S ACRONYM(S)<br><br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><br>Approved for public release; distribution is unlimited. | | | | | | |
| 13. SUPPLEMENTARY NOTES | | | | | | |
| 14. ABSTRACT<br><br>Protection afforded by a respiratory filter depends on chemical or biological agent and flow rate. Filtration mechanisms such as chemical adsorption depend on sufficient residence time for the filter media to extract noxious agents from the airstream. Consequently, filter efficiency is a function of inspiratory air velocities. Filter designs account for this by adjusting bed depth and cross-sectional area to anticipated flow rates. The NATO-standard military filter (C2A1) and many commercial filters are designed and tested at 32 liters/min (lpm). The present study investigated respiratory demand while U.S. Marines (n=32) completed operationally relevant tasks in MOPP IV chemical protective ensembles (including M-40 masks and C2A1 filters). Respiratory demand greatly exceeded current test conditions during the most arduous tasks; minute ventilation = 96.4 ± 18.9 lpm (mean ± SD) with a maximum of 131.7 lpm observed in one subject. Mean peak inspiratory flow rate (PIF) reached 238.7 ± 34.0 lpm with maximum PIF often exceeding 300 lpm (maximum observed value = 356.3 lpm). The observed respiratory demand was consistent with data reported in previous laboratory studies imposing very heavy workloads. This study is among the few to report on respiratory demand while subjects perform occupationally relevant tasking in chemical protective ensembles. The results indicate that military and industrial filters will probably encounter higher flow rates than previously anticipated during heavy exertion. | | | | | | |
| 15. SUBJECT TERMS<br><br>Body cooling; air conditioning; heat stress; liquid cooling | | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON<br>Jonathan W. Kaufman, Ph.D. | |
| a. REPORT<br><br>Unclassified | b. ABSTRACT<br><br>Unclassified | c. THIS PAGE<br><br>Unclassified | SAR | 51 | 19b. TELEPHONE NUMBER (include area code)<br>(301) 342-8883 | |

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

## EXECUTIVE SUMMARY

**Findings**: Respiratory flow rates and heart rates (HRs) were obtained from U.S. Marine Corps Chemical Biological Incident Response Force (CBIRF) personnel while they engaged in the Fire Service Joint Labor Management Wellness/Fitness Initiative Candidate Physical Ability Test, a firefighter agility test. Given that the goal of this study was to quantify maximum respiratory flows during operational-relevant physical exertion, data in table 1 were obtained from the region of peak respiratory effort generally observed in each trial. This period of peak respiratory effort lasted 2.8 ± 1.6 min (mean ± standard deviation (std. dev.)).

Table 1: Mean and peak physiological responses to heavy exertion while participating in a firefighter agility test. Data generally reflect measurements obtained during the period of peak respiratory effort. All variables derived from respiratory volumes are corrected to Body Temperature Pressure Saturation (BTPS) conditions.

| Variable | Units | Mean | Std. Dev. | Maximum |
|---|---|---|---|---|
| Minute ventilation, $\dot{V}_I$ | lpm | 96.4 | 18.9 | 131.7 |
| Mean peak inspiratory flow, $\overline{PIF}$ | lpm | 238.7 | 34.0 | 301.9 |
| Maximum peak inspiratory flow, $PIF_{max}$ | lpm | 294.0 | 38.6 | 356.3 |
| Breathing frequency | Breaths/min | 41.1 | 6.6 | 56.4 |
| Tidal volume, $V_t$ | Liters | 2.46 | 0.55 | 4.5 |
| Inhalation time, $T_i$ | sec | 0.9 | 0.14 | 1.2 |
| Total breath cycle time, $T_{tot}$ | sec | 1.5 | 0.25 | 2.0 |
| Duty cycle, $DC = T_i/T_{tot}$ | | 0.6 | 0.04 | 0.7 |
| Mean HR, $\overline{HR}$ | Beats/min | 162.9 | 10.8 | 183.4 |
| Maximum HR, $HR_{max}$ | Beats/min | 171.7 | 13.0 | 194 |

**Study Conclusions**

1) Respiratory flow rates generated while completing physically demanding tasks are considerably higher than flow rates used to assess filter efficacy.
2) Results generally conform to existing literature regarding respiratory demand for individuals wearing an APR while performing high workloads near $\dot{V}O_{2max}$.
3) The instrumentation used in this study was effective in acquiring continuous physiological field data under daunting conditions. Despite this, future studies need to account for significant data losses due to instrumentation failure.
4) This work explored breathing demand while performing short, high exertion tasks but how this compares to longer duration tasks remains unknown.
5) Marines (especially CBIRF members), soldiers, and certain industrial workers are familiar with using respirators due to frequent training and use. Other military personnel and industrial workers, however, use respirators only intermittently. Consequently, their breathing demands may differ from these findings when required to use respirators in a field environment due to anxiety or inexperience.

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## ACKNOWLEDGEMENTS

The author would like to thank CBIRF and Marine Corps Systems Command for their support in this endeavor. The highest praise goes to the individuals who volunteered to undergo the physically demanding testing. Without their fortitude, this study would have been impossible. The support staff at the CBIRF training center, including both civilian and military personnel, was also outstanding. Three individuals merit special thanks. Sam Pitts made this study happen and was responsible for developing the concept and acquiring support for this study. Dr. Karen Coyne and MSTC A. J. St. Germaine, ostensibly attending the trials as observers, provided unsolicited help at critical moments and made significant contributions to data integrity. In addition, David Caretti and Richard Newton made significant contributions to the scientific content of this work. I would like to also thank the NAVAIR team for exemplary work: J. J. Armstrong, HMCS Stephen Coleman, Earl Kauffman, HM1 Denise Mercado, HMC Dan Shaller, and LT Deborah White. Sherri Hastings has also done yeoman work with the statistics.

Despite all of this assistance, any errors or oversights are entirely the responsibility of the author.

## INTRODUCTION

Efficiency in fixed-bed chemical filters commonly used in commercial and military air-purifying respirators (APRs) is highly dependent on residence time. The residence time is the length of time for a molecule to traverse the filter bed. The longer a molecule resides in the filter bed, the greater the likelihood it will be adsorbed or reacted. Residence time decreases as the velocity of the air stream increases. The velocity of the air stream through a filter is the volumetric flow rate divided by the cross sectional area of the filter. Hence, as the volumetric flow rate through the filter increases, the breakthrough time or life of the filter decreases. Therefore, excessive flow rates can overwhelm a filter bed increasing the risk of injury to the APR user.

Typical APR design primarily exposes filters to chemical contaminants during inspiration since a separate pathway (exhalation valve) directs expired air out of the APR. Two respiratory variables are commonly used to correlate APR performance to human inhalation; minute ventilation ($\dot{V}_I$) and peak inspiratory flow (PIF). Minute ventilation describes the quantity of air inspired (or expired) over a 1-min period and relates directly to airborne toxins filter loading in a contaminated atmosphere. PIF describes the highest flow rate achieved during inspiration and correlates directly with airstream velocity. Removing contaminants from the inspired airstream by chemical adsorption or reaction with the carbon filter bed may be adversely affected by increased PIF because of reduced residence times within the filter.

Designing appropriate chemical filters for occupational use depends on the anticipated respiratory demands produced by related tasks. For example, a filter designed for a sedentary worker (e.g., machine operator) would likely be inadequate for a physically active worker (e.g., HAZMAT cleanup crew). Consequently, characterizing representative respiratory demand is crucial for designing and testing chemical filters intended for a specific occupational population. Unfortunately, there is a dearth of data available for respiratory airflows in an actual occupational setting, particularly where the greatest demands are placed on APR chemical filters, i.e., physically demanding tasks.

Current testing criteria use a steady flow of 32 liters per minute (lpm) as the basis for filter assessment during exposure to a variety of chemical warfare agents, toxic industrial chemicals, and toxic industrial materials. Recent concerns suggest that this may underestimate actual respiratory demands during field use and thus filters tested to this criterion may not provide adequate protection to the user. This study was intended to quantify respiratory demands in U.S. Marine Corps Chemical Biological Incident Response Force (CBIRF) personnel performing mission-related tasks.

## METHODS

This study was intended to quantify respiratory function in Marines performing operationally relevant tasks while wearing chemical/biological protection typically used in the field. Subjects performed physical tasks on three consecutive days. A variety of problems caused day one to serve as a shakedown for the subsequent experimental trials on Days 2 and 3. The

subject pool was split into two groups on Day 2 with groups completing either a simulated decontamination (DECON) process or a reconnaissance (RECON) patrol to represent light/moderate workload tasks. Each task (DECON or RECON) took 60 min to complete. Day 3 had all participants performing a modified version of the Fire Service Joint Labor Management Wellness/Fitness Initiative Candidate Physical Ability Test (CPAT), high workload tasks taking approximately 15 min to complete (table 2).

Table 2: Description of the eight events comprising the Fairfax County, VA CPAT employed by this study. Test modifications were included to tailor the test to reflect CBIRF operational tasks. Walking distance between events was approximately 85 ft. Photos depicting each task are found in appendix A.

| Event | Name | Purpose/Simulation | Description | Nominal Duration (sec) |
|---|---|---|---|---|
| 1* | Stair Climb | Climbing stairs in full protective gear while carrying equipment | 1. Load subject with 50 lb of additional weight<br>2. 20-sec warmup on stepping machine at rate of 50 steps/min<br>3. Step for 3 min at 60 steps/min | 200 |
| 2 | Hose Drag | Dragging uncharged hose around obstacles | 1. Carry hose 200 ft, turn 90 deg around obstacle, and carry additional 25 ft<br>2. Stop and drag an additional 50 ft of hose from kneeling position | 40 |
| 3 | Equipment Carry | Removing power tools from vehicle and transporting to emergency site | Lift two saws from stand, walk 75 ft around drum, return to start, place saws back on stand | 30 |
| 4a | Ladder Raise | Raise ladder rung by rung | Raise and lower 24 ft ladder | 40 (4a&4b) |
| 4b* | Hose Hoist | Raise ladder by lanyard | Raise and lower full hose reel approx. 30 ft | |
| 5 | Forcible Entry | Breaching wall or locked door | Strike measuring device with 10 lb until 700 lb cumulative exerted | 30 |
| 6* | Search | Search for victim in unpredictable area with limited visibility | Crawl through dark 80 ft tunnel maze containing obstacles and narrowed passageways | 150 |
| 7 | Rescue | Removing victim from emergency scene | Drag 165 lb mannequin 35 ft, turn 180 deg around drum, return to start. | 30 |
| 8 | Ceiling breach and pull | Breaching and pulling down ceiling to check for fire | Using pole pike<br>1. Lift 60 lb hinged door three times<br>2. Pull down hinged plate five times<br>3. Complete four sets | 60 |
| | * - modification of Fairfax County, Virginia, CPAT (event No. 1 – 25 lb of additional weight; 4b – hoist hose instead of ladder; 6 – 16 ft additional length, one additional 90 deg turn) | | | |

***Subjects***: Forty-eight CBIRF members (table 3) volunteered to participate after being fully informed of the details of the experiment protocol and associated risks. The human use protocol had been reviewed and approved by the Naval Air Systems Command Institutional Review Board prior to subject consent. Baseline pulmonary health and physical fitness were assessed in each subject with a pulmonary function test (Pulmonary Data Service Instrumentation, Louisville, CO, model Koko spirometer) and submaximal oxygen consumption test (Forestry Step Test (reference 1) (table 3).

Table 3: Subject physical characteristics and pulmonary function test results.

| | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| **Physical parameters** | | | | |
| *Age, years* | 22.0 | 2.1 | 19 | 29 |
| *Height, cm* | 178.3 | 6.7 | 162.6 | 190.5 |
| *Weight, kg* | 80.3 | 10.3 | 62.7 | 109.1 |
| *Maximum oxygen consumption* $(\dot{V}O_{2\max})$, *L/min* | 48.7 | 6.1 | 35 | 63 |
| **Pulmonary function parameters** | | | | |
| *Forced vital capacity (FVC), L* | 5.29 | 0.91 | 3.12 | 7.33 |
| *Forced expired volume in 1 sec* $(FEV_{1.0})$, *L* | 4.41 | 0.77 | 2.74 | 6.07 |
| $FEV_{1.0}/FVC$ | 0.84 | 0.06 | 0.66 | 0.96 |
| *Peak expired flow rate (PEFR), L/sec* | 9.41 | 2.51 | 4.84 | 17.07 |
| *Forced expiratory flow* $(FEF_{25\text{-}75\%})$, *L/sec* | 4.90 | 1.73 | 2.15 | 11.69 |
| *Forced inspired vital capacity (FIVC), L* | 5.14 | 0.85 | 3.11 | 7.30 |
| *Forced inspired volume in 1 sec* $(FIV_{1.0})$, *L* | 4.55 | 1.15 | 0.72 | 7.22 |
| $FIV_{1.0}/FIVC$ | 0.91 | 0.12 | 0.52 | 1.00 |
| *Peak inspired flow rate (PIFR), L/sec* | 6.08 | 1.85 | 2.84 | 12.37 |
| *Forced inspiratory flow* $(FIF_{25\text{-}75\%})$, *L/sec* | 5.47 | 1.87 | 2.50 | 11.67 |

***Materials***: Each subject wore standard MOPP 4 gear (Saratoga) with an APR (M-40 mask with C2A1 filter) during all trials. The pressure drop across a new C2A1 cartridge was 5.20 cm $H_2O$. In addition, web gear (782 gear) was worn with pockets to carry instrumentation. The total weight of this gear was 11.0 ± 0.5 kg. An additional 22.7 kg (50 lb) weighted vest was worn throughout the CPAT trials and augmented by a load of 22.7 kg (50 lb) during CPAT event No. 1 (stair climb).

***Instrumentation***: Respiratory flow rate data were measured continuously during trials with a turbine flow meter (Interface Associates, Laguna Niguel, CA, model VMM-401 with adult large turbine flow element, nominal range 0-720 lpm) and recorded at a rate of 50 Hz (Fourier Systems, Atlanta, GA, model MultiLog data logger). Flow meters were calibrated with a flow

rate calibrator (Timeter, Lancaster, PA, model RT-200) and checked against a computer-controlled sinusoidal breathing machine (Krug Inc., San Antonio, TX). Heart rate (HR) was recorded at a rate of 0.2 Hz with a HR monitor (Polar Electro, models Accurex and Xtrainer). Ambient air temperature ($T_{air}$), relative humidity (RH), and barometric pressure ($P_{air}$) were measured with a hand-held humidity sensor (Vaisala, Helsinki, Finland, model HMI 41) and barometer (Vacumed, Ventura, CA, model Barotemp).

***Experimental Methods***: DECON tasks consisted of simulated decontamination procedures employed when CBIRF establishes a field DECON line. This includes various tasks including lifting and moving litters and washing down individuals (figure A-2). RECON tasks involved a reconnoitering of the surrounding area. This involved walking through various environments including buildings, building debris, open fields, and Woods (figure A-3). CPAT trials involved a variety of simulated firefighting tasks (table 2 and figures A-4 through A-12) of a physically demanding nature.

Subjects entered the air-conditioned dressing area (table 4) between approximately 8 AM and 3 PM, were fitted with a HR monitor, and dressed in a MOPP 4 ensemble. Each subject was given a new C2A1 filter (fresh out of the storage container) that was fitted with a turbine flow element (figure 1). Filters gained 5.2 ± 2.2 g of water on Day 2 and 6.6 ± 2.2 g of water on Day 3. Connections were then made between the flow element and meter and between the meter and data logger. Data collection was initiated at the start of a pretrial 5-min rest period. Subjects walked out of the dressing area and into the testing areas at the conclusion of the rest period. Table 4 gives the environment conditions in the semi-enclosed test area for each day (RECON teams walked outside of this area for varying times though conditions were probably not appreciably different). Groups of four were started together during Day 2 so that an entire DECON or RECON 4-person team could begin their tasks together. Day 3 starting times for individual subjects were staggered by 5-min intervals to avoid queuing at task stations.

Table 4: Environmental conditions measured at the dressing and testing areas during Days 2 and 3. ($P_{air}$ = barometric pressure, $T_{air}$ = air temperature, RH = relative humidity)

| Day | | Dressing Area | | Test Area | |
|---|---|---|---|---|---|
| | $P_{air}$ | $T_{air}$ | RH | $T_{air}$ | RH |
| 2 - AM | 752 | 23.4 | 59.5 | 22.9 | 78.0 |
| 2 - PM | 751 | 23.0 | 62.3 | 25.4 | 60.6 |
| 3 - AM | 752 | 19.6 | 62.1 | 20.9 | 77.5 |
| 3 - PM | 752 | 22.2 | 70.5 | 23.7 | 63.2 |

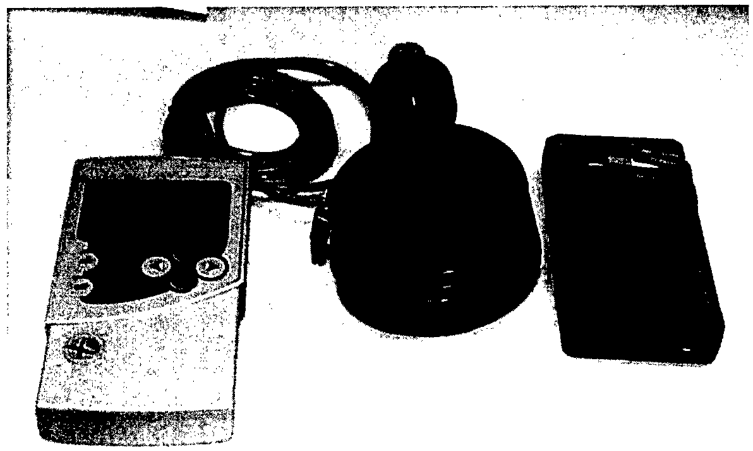


Figure 1: Flow transducer attached to a C2A1 filter. Also shown are the flow meter (right) and data logger (left) used to collect data during trials. The Polar heart monitor is not shown.

***Data Analysis***: Day 2 data generally consisted of two distinct regions (figure 2); rest and exertion. To assess possible differences due to time, Day 2 data were divided into periods of 0-5 min (R-2), 5-16.7 min (P1), and 17-33 min (P2). Data for time periods >33 min were not analyzed because of the quantity of missing data.

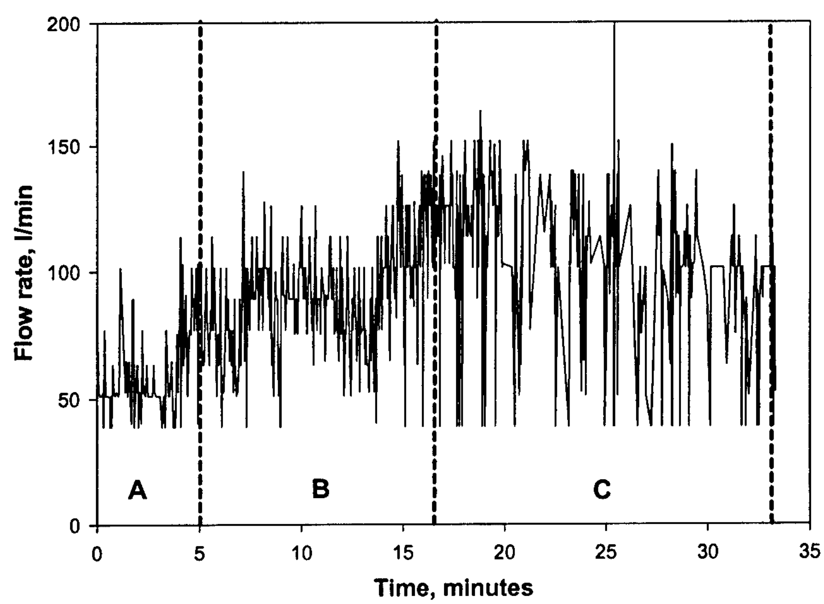



Figure 2: Typical inspiratory peak flow during a DECON trial. Periods of elevated flow probably relate to physical exertion (e.g., lifting a "victim" upon the decontamination table). Rest occurred during the first 5 min (A) followed by various physical tasks. Data were analyzed for two arbitrary activity segments; period P-1, 300-1000 sec (B) and period P-2, 1000-2000 sec.

Day 3 data generally consisted of 4-5 regions (figure 3); low plateau (pretask rest), steep slope (start of exertion), peak (maximum exertion generally associated with CPAT event No. 1), high plateau (CPAT event Nos. 2-7 or 8), and sometimes a second peak (CPAT event No. 8). The effects of physical exertion were analyzed by comparing data from the initial rest period (R-3) (0-5 min), peak exertion, and the final exercise (FE) period (final 3 min). Given that the goal of this study was to quantify maximum respiratory flows during physical exertion, a Region of Peak Respiration (RPR) was identified corresponding to the period of greatest respiratory efforts and generally correlated to the first peak, i.e., end of the first CPAT event (stair climber) (figure 4). To find each trial's RPR, each flow rate profile was visually assessed to identify the region with the highest peaks. The 10 highest peak values from within this region were determined and a mean calculated for all peaks within this region having these values. Times associated with the initial and final peaks within this region corresponding to ±80% of this mean defined the RPR lower and upper time limits.

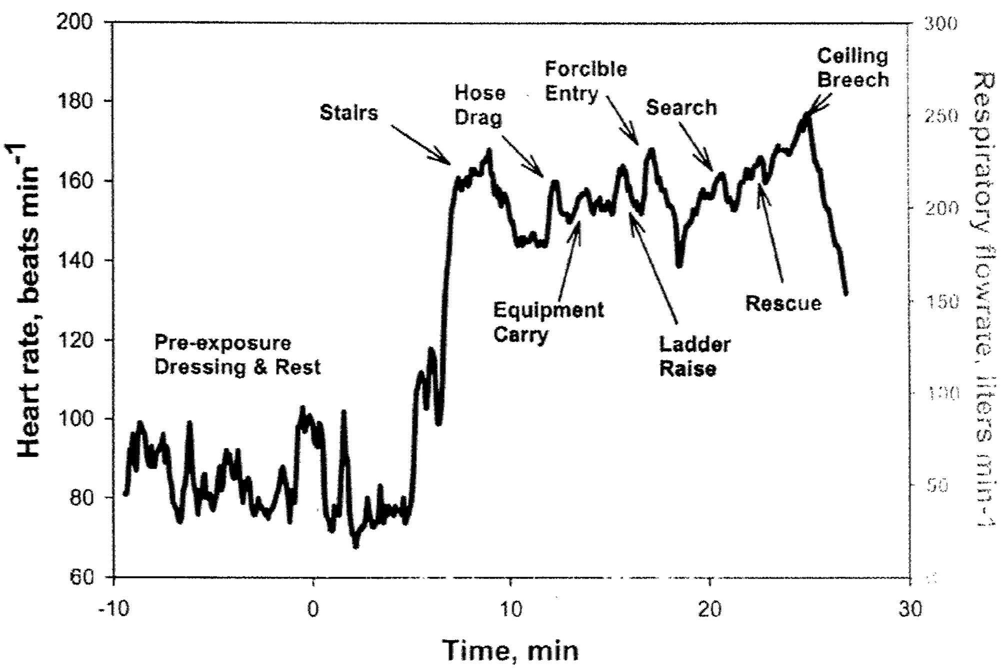



Figure 3: Typical HR (black line) and respiratory flow rate (grey areas) data showing the relationship between physiological responses and physical tasks. Respiratory data represent only inhalation; measurements were only obtained from the inspiratory side of the air-purifying respirator.

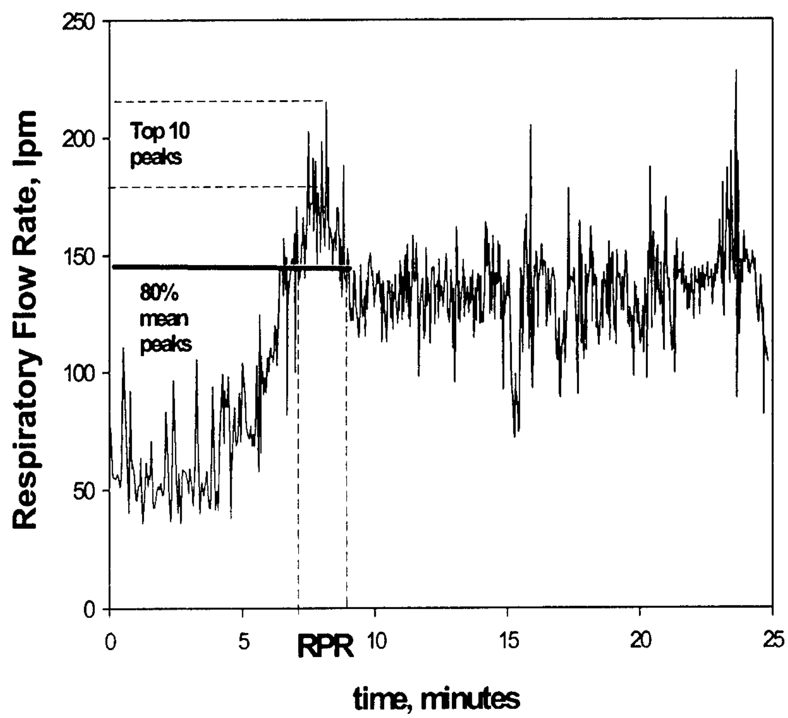



Figure 4: Depiction of the RPR determined from a typical respiration curve. Data shown were only the inspiratory peaks from each breath. RPR is derived from the region of greatest respiration and not necessarily based on the highest absolute peak.

PIF was identified for each breath by finding the local maximum value between the leading and trailing zero crossing points (figure 5). These bounds (start and end of each inhalation) were used to calculate inhalation time ($T_i$), total breath time (inhalation and exhalation) ($T_{tot}$), and the duty cycle (DC) = $T_i/T_{tot}$ (i.e., what percentage of a breath is taken up by inhalation time). Breathing frequency, *f*, was calculated by dividing the number of peaks in a given time period by the total duration of that period. Mean tidal volume ($V_t$), was quantified by taking the sum of each integrated area between the start and end of inhalation and dividing by duration and breathing frequency. $\dot{V}_I$, reflecting inspiratory airflow during complete breaths, quantified airflow through filters during trials.

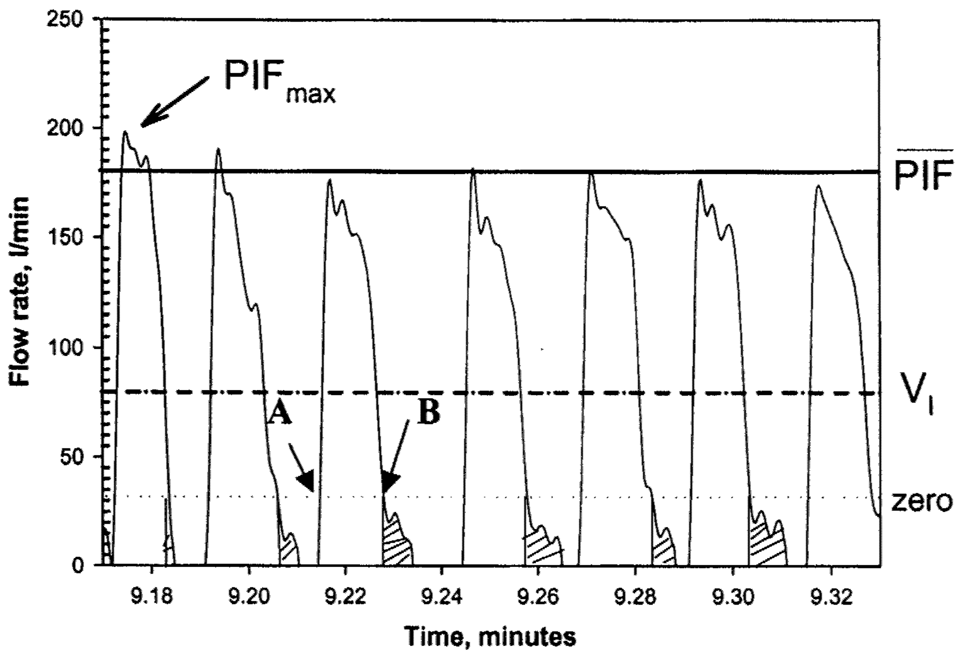



Figure 5: Typical inspiratory curves obtained during a period of heavy exertion. Line marked by "zero" identifies the start (point A) and end (point B) time limits used to bound individual breaths and define their duration. Flow indicated by shaded region is attributable to flow meter impeller inertia. $PIF_{max}$ indicates the local maximum for this data set whereas $\overline{PIF}$ represents the mean of individual breath peaks. $\dot{V}_I$ indicates the minute ventilation for this set of breaths.

A mean PIF was calculated at each analyzed time period (i.e., Day 2 = R-2, P1, P2; Day 3 = R-3, RPR, FE) for each individual trial (figure 5) and then an overall mean across subjects, $\overline{PIF}$, was calculated as the mean of the individual trial means

$$\overline{PIF} = \frac{\sum_i \overline{PIF}_{i,t}}{n_i} \tag{0.1}$$

where $\overline{PIF}_{i,t}$ = the mean PIF for a given subject trial, i, during a specific time period, j, and $n_i$ = the number of recorded trials. The maximum $\overline{PIF}_{i,t}$ was also reported. In addition, the mean across subjects of the largest PIF observed during individual trials and time periods was reported ($PIF_{max}$, figure 5)

$$PIF_{max} = \frac{\sum_i PIF_{max\,i,j}}{n_i} \tag{0.2}$$

where $PIF_{max\,i,j}$ = the maximum observed PIF.

Mechanical work associated with respiration depends on the shape of the respiratory wave, with rectangular or trapezoidal waveforms requiring less energy than the sinusoidal waveform commonly associated with respiration (references 14 and 16). Johnson (reference 14) suggests that the waveform shape changes as a function of exertion, transitioning from sinusoidal during resting or light exercise to rectangular or trapezoidal during heavy exercise. Inspiratory waveforms were assessed by fitting inspiratory curves to sinusoidal and double sigmoidal curves (TableCurve, version 4.0). Double sigmoidal curves were chosen because they reflect the waveform shape produced during physiological breathing in a rectangular or trapezoidal pattern (figure 6).

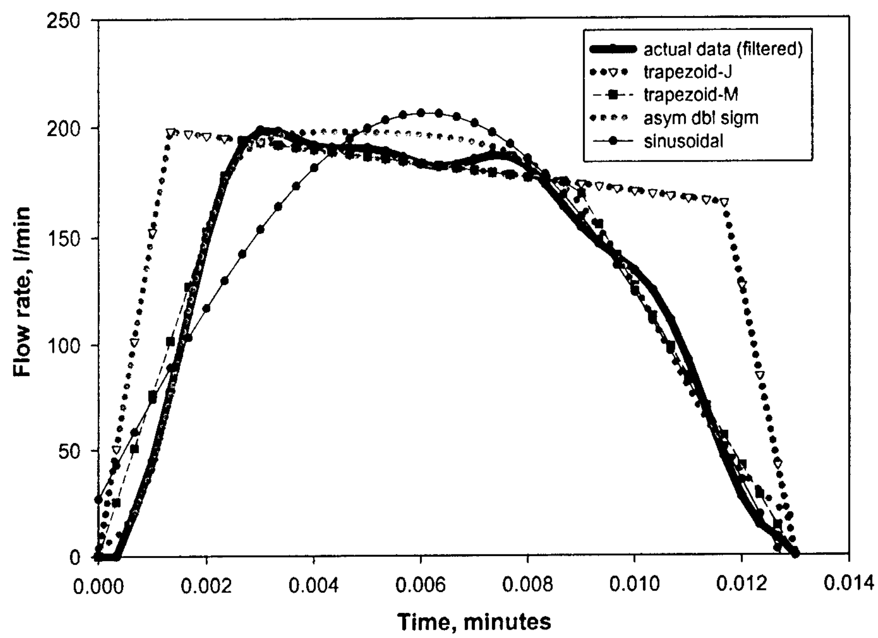



Figure 6: Typical inspiratory curve fitted to asymmetric double sigmoidal, sinusoidal, and trapezoidal models. The coefficient of determination, $r^2$, for the asymmetric double sigmoid model = 0.985 and for the sinusoidal model = 0.905. The two trapezoidal models differ in their coefficients; trapezoid-J employs the parameters used by Johnson (reference 14) while trapezoid-M modifies these parameters to fit the data more closely.

A small subset of the thousands of inspiratory waveforms collected was selected to assess waveform shape. Five trials were selected and the first five inspiratory waves observed after 100 sec into both the rest period and RPR were analyzed (total of 50 waveforms). Inspiratory flow rate, $\dot{V}$, was fitted to sinusoidal breathing according to the equation

$$\dot{V} = a_0 V_m \sin\left(\frac{a_1 \pi}{T_{tot}} t + a_2\right) \tag{0.3}$$

where $V_m$ = peak flow within that breath, $T_{tot}$ = breath duration, t = time within the breath, and $a_i$ = fitted parameters. Breathing patterns reflecting a double sigmoidal pattern were fitted to the equation

$$\dot{V} = \left(\frac{V_m}{1+\exp\alpha}\right)\left(1 - \frac{1}{1+\exp\beta}\right) \tag{0.4}$$

where

$$\alpha = \frac{-t - a_0 - a_1/2}{a_2} \tag{0.5}$$

and

$$\beta = \frac{-t - a_0 - a_1/2}{a_3} \tag{0.6}$$

The ratios $\frac{\overline{\mathrm{PIF}}}{\dot{\mathrm{V}}_\mathrm{I}}$ and $\frac{\mathrm{PIF}_{\mathrm{max}}}{\dot{\mathrm{V}}_\mathrm{I}}$ were also used to assess differences between waveform shape during rest and exertion.

Respiratory data were filtered (low pass Butterworth 8 pole filter with a 6 Hz cutoff) prior to analysis to remove electronic noise. Respiratory volumes, along with all derived variables (e.g., $\dot{\mathrm{V}}_\mathrm{I}$), were corrected to BTPS conditions. Mean and peak HR was analyzed in an analogous manner to respiratory data.

***<u>Statistical Analysis</u>:*** Day 2 data were analyzed with a two-way repeated measures Analysis of Variance (ANOVA), with Type (RECON or DECON) as one factor and Time (level 1 = R-2, level 2 = P1, level 3 = P2) as the repeated measure. Contrast analysis was used to identify those configurations which differed significantly from the others when the ANOVA detected significant differences among configurations. Differences between Day 3 data obtained during R-3, RPR, and FE were compared using a repeated measures MANOVA. Linear correlation analysis (Pearson Product-Moment correlation) was used to assess relationships between respiratory variables and pulmonary function and physical parameters. Where correlations were identified, multiple regression was used to establish predictive equations for $\dot{\mathrm{V}}_\mathrm{I}$, $\overline{\mathrm{PIF}}$, and $\mathrm{PIF}_{\mathrm{max}}$. A paired-t test was used to assess prediction validity by comparing actual to predicted values. The Kruskal-Wallis one-way ANOVA on ranks was used to identify significant differences among $PIF/\dot{V}_i$ ratios. Dunn's method for multiple comparisons was used when

differences were identified. A parametric ANOVA was not used because the test for normally distributed data failed. Paired-t tests were used to compare the closeness-of-fit ($r^2$) obtained from fitting inspiratory waveforms to sinusoidal and double sigmoidal models. Power calculations ($1-\beta$) were performed to determine whether sample size of waveforms were analyzed to rely on the results. A variety of instrumentation problems reduced the useable sample size on both test days so that $n = 28$ to 32. Data were reported as mean values ± standard deviation (std. dev.). Differences were considered significant at the $\alpha = .05$ level.

## RESULTS

The intent of this study was to quantify respiratory demand during operationally relevant tasks. According to CBIRF Noncommissioned Officers and experienced trainers, the physical tasks employed in the DECON, RECON, and CPAT events closely mirror some CBIRF operational tasks. Physical exertion during Day 2 trials (both DECON and RECON) lasted for 60 min compared to 19.2 ±4.1 min during Day 3. Both Day 2 and Day 3 trials included a 5-min rest period prior to exertion. Day 3 RPR lasted for a period of 2.8 ±1.6 min.

Respiratory responses reflected the physical demands placed on participants. Mean $f$, $\dot{V}_I$, and $V_t$ increased significantly as workload increased from rest to either light/moderate or heavy exertion ($p<0.001$) and from light/moderate to heavy workloads ($p<0.001$) (figures 7, 8, and 9). The constant 32 lpm flow rate used for existing filter testing is much lower than the mean and maximum $\dot{V}_I$ observed during RPR and FE ($p<0.001$) (table 5 and figure 10). Likewise, peak inspiratory flow ($\overline{PIF}$ and $PIF_{max}$) increased significantly as a function of exertion ($p<0.001$) (figures 11 and 12).

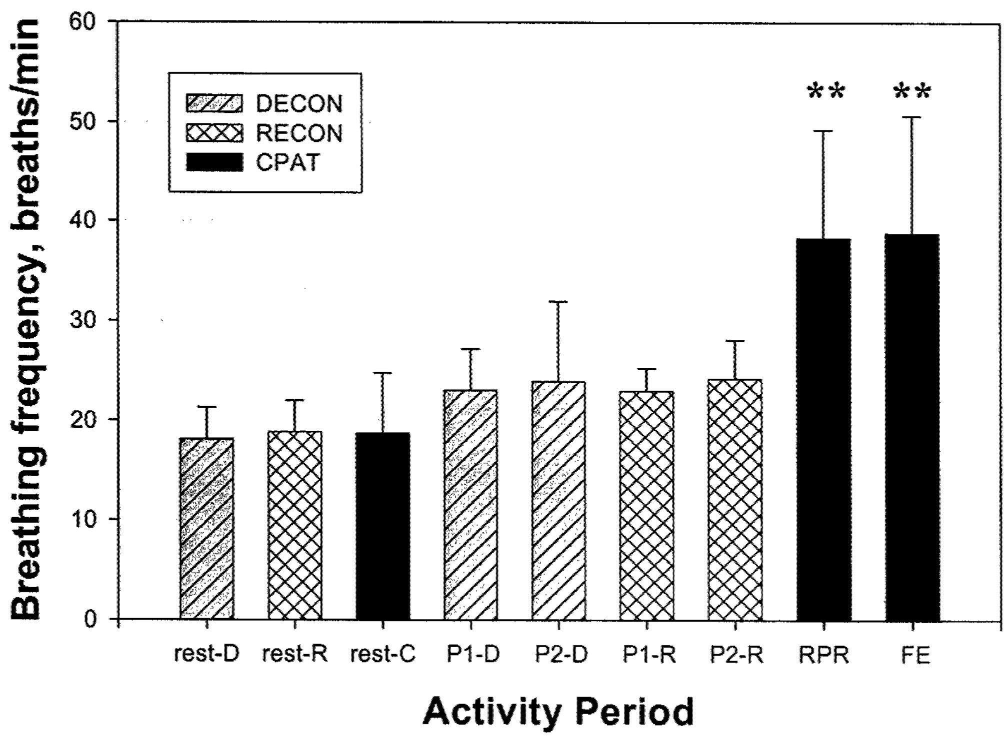



Figure 7: Breathing frequency measured during each activity period. Mean ± std. dev. (** - p < 0.01) D = DECON, R = RECON, C = CPAT, RPR = region of peak respiration, FE = final exercise period.

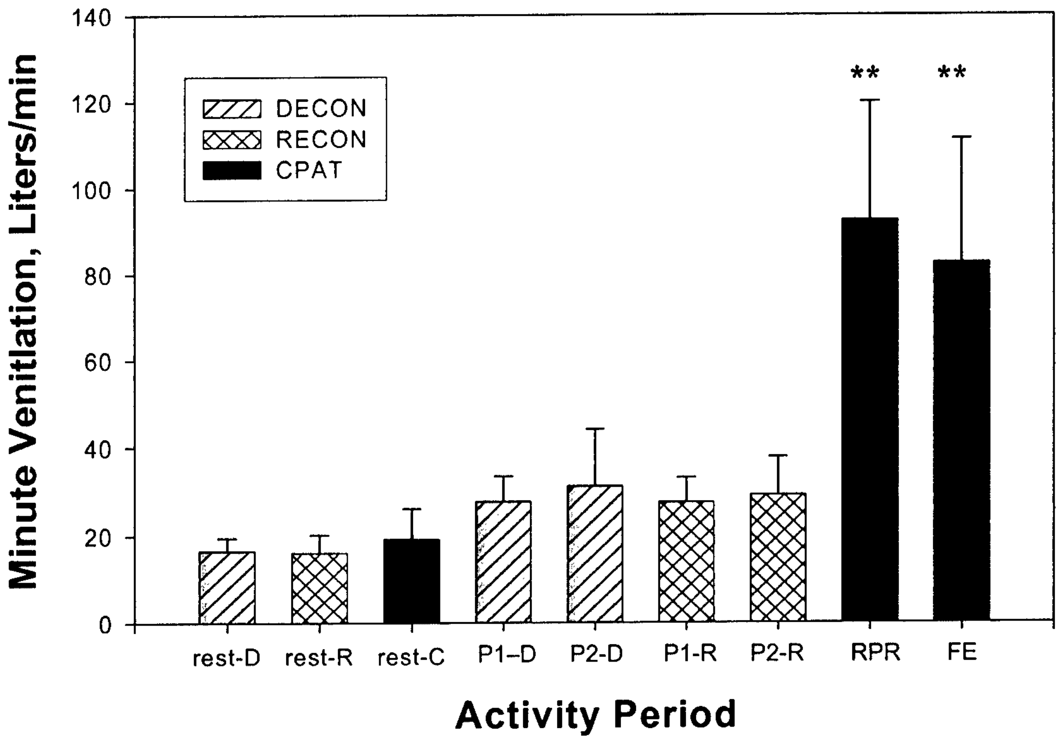



Figure 8: Minute ventilation observed during each activity period. Mean ± std. dev. (** - $p<0.01$)

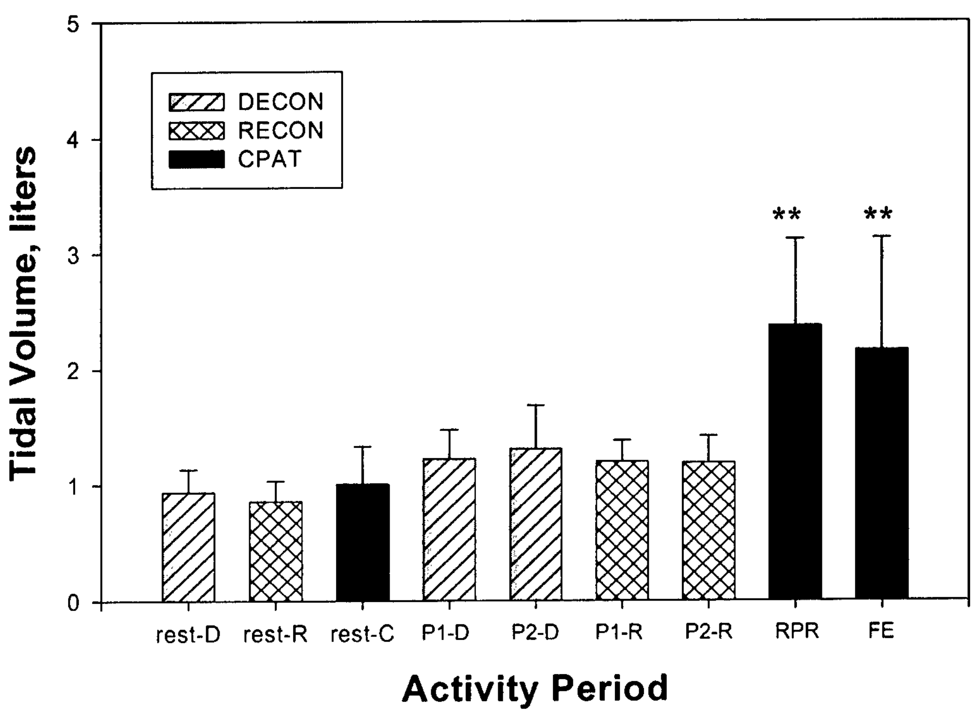



Figure 9: Tidal volume measured during each activity period. Mean ± std. dev. (** - $p < 0.01$)

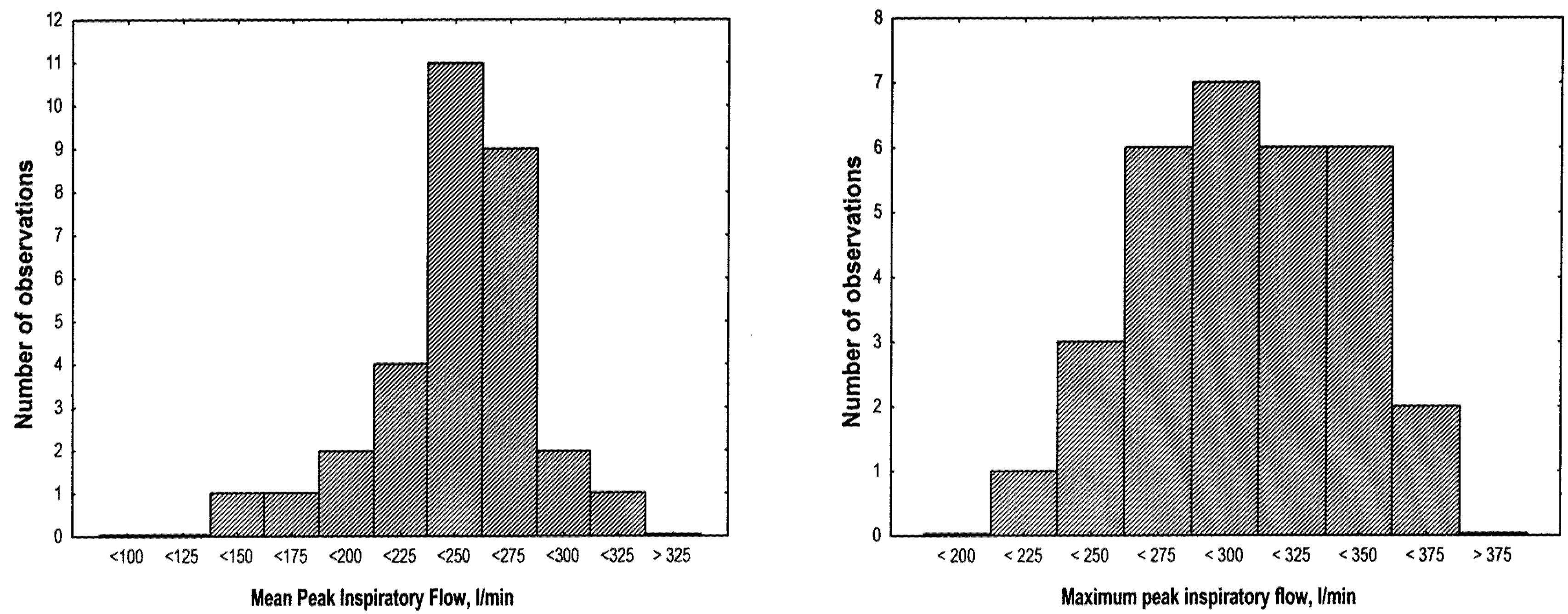
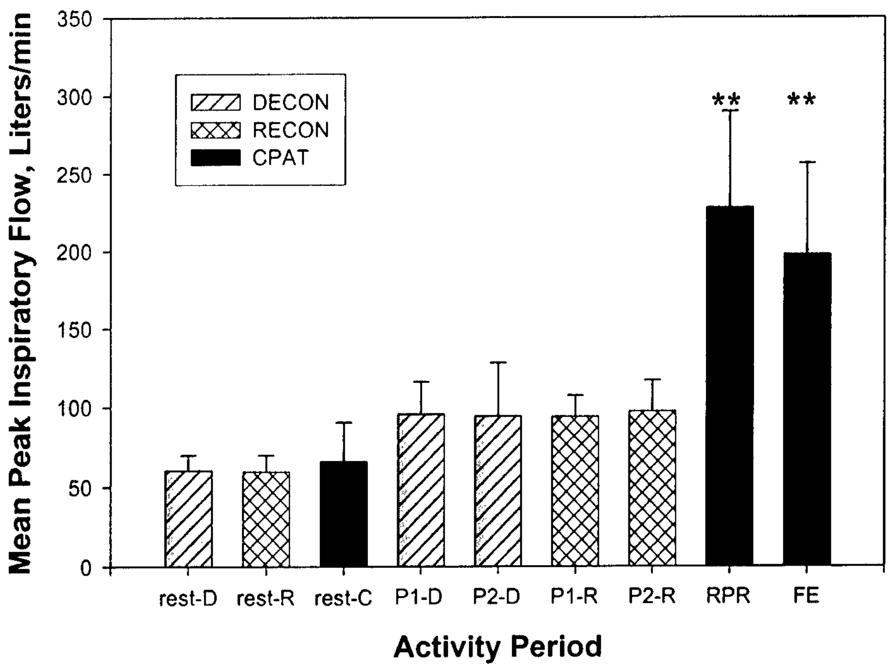



Figure 10: Mean and maximum peak inspiratory flow rates observed within the RPR. Note that $PIF_{max}$ exceeded 300 lpm in nearly half of subjects.



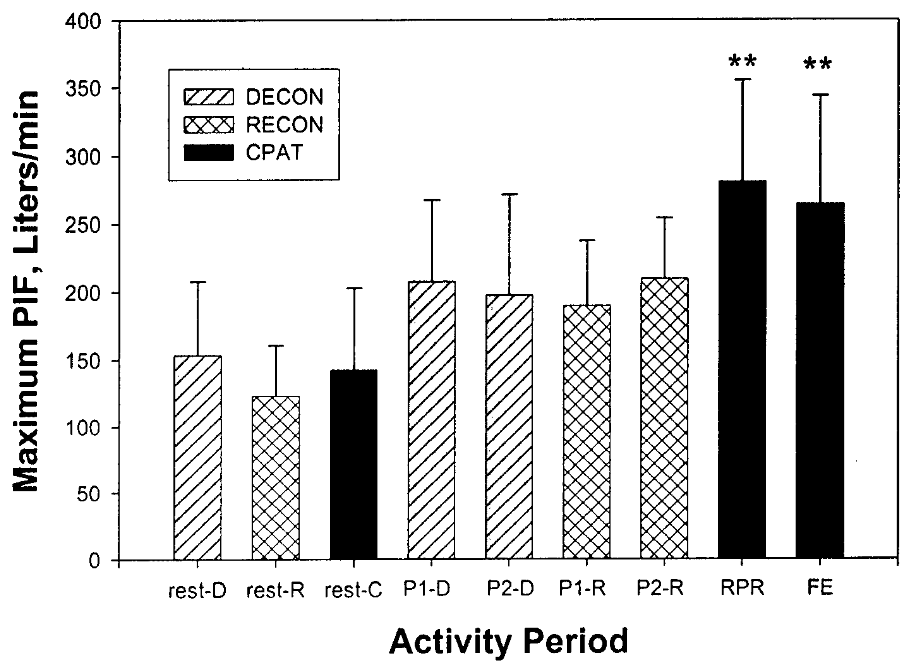




Figure 11: Mean *(upper figure)* and maximum *(lower figure)* peak inspiratory flow rates (mean and maximum) observed during each activity period. Mean ± std. dev. (** - $p<0.01$)

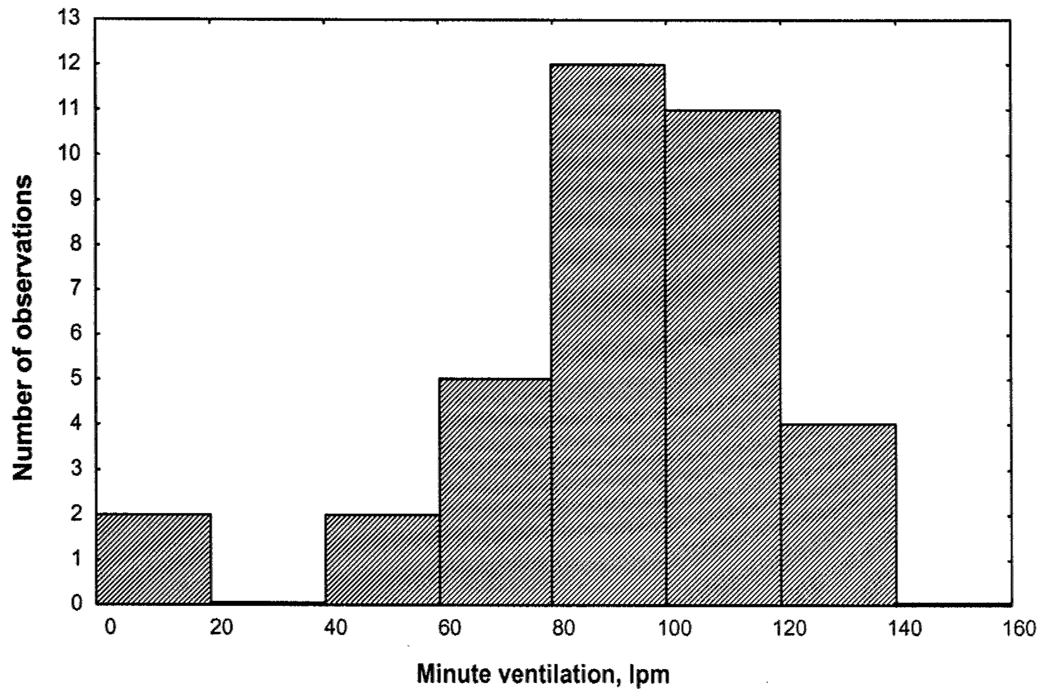



Figure 12: Minute ventilation observed within the RPR. Note that $\dot{V}_I$ exceeded 100 lpm in 42% of subjects.

Table 5: Maximum observed values over Day 2 and Day 3 trials. Data generally represent RPR values except for FE values designated by *. Note that overall RPR and FE data were roughly comparable. Data in parenthesis provide corresponding RPR values.

| Respiratory Variable | | Mean | Std. Dev. | Maximum |
|---|---|---|---|---|
| $\dot{V}_I$ | lpm | 96.4 | 18.9 | 131.7* (130.3) |
| $V_t$ | liters | 2.46 | 0.55 | 4.5* (3.6) |
| $\overline{PIF}$ | lpm | 238.7 | 34.0 | 301.9 |
| $PIF_{max}$ | lpm | 294.0 | 38.6 | 356.3 |
| $f$ | breaths/min | 41.1* (39.9) | 6.6* (6.7) | 56.4 |

Changes in respiratory timing also reflected increased exertion. Significantly deeper breathing (i.e., longer $T_{tot}$) was observed at rest (R-2 (DECON and RECON), R-3) than during light to moderate work (P1, P2) ($p<0.001$) (tables 6 and 7). The greater exertion required during RPR and FE produced much shallower breather (i.e., shorter $T_{tot}$) than either rest or light to moderate exertion ($P<0.001$). Only during RPR and FE was TI significantly shortened ($p<0.001$). Curiously, DC, increasing significantly as subjects moved from rest to exercise ($P < 0.001$), did not differ significantly between light and heavy workloads (P1 vs. RPR).

Statistically significant differences in HR were generally not observed between P1 and P2 or between RPR and FE (figure 13). HR (especially $HR_{max}$), however, continued to increase significantly over the course of exposures, particularly on Day 3 ($p<0.01$). Figure 13 shows that physical stress, as reflected by HR, was significantly greater during CPAT exercise periods (RPR and FE) then either DECON or RECON ($P<0.01$).

Significantly smaller $\frac{\overline{\mathrm{PIF}}}{\dot{\mathrm{V}}_\mathrm{I}}$ and $\frac{\mathrm{PIF}_{\max}}{\dot{\mathrm{V}}_\mathrm{I}}$ ratios were observed during RPR and FE compared with R-2, R-3, P-1, or P-2 ($p < 0.05$) (table 8). No significant difference between RPR and Fe or between R-2, R-3, P-1, and P-2 was observed. Consequently, R-3 and RPR were used as representative periods for assessing goodness-of-fit. Fitting a double sigmoidal model to both resting ($r^2 = 0.934 \pm 0.076$) and RPR ($r^2 = 0.981 \pm 0.021$) data produced significantly better goodness-of-fit than a sinusoidal model during rest ($r^2 = 0.807 \pm 0.115$) or RPR ($r^2 = 0.850 \pm 0.073$) ($p<0.0001$). Goodness-of-fit was also significantly better during RPR than rest with the double sigmoidal model ($p<0.01$). Visual assessment of waveform shape indicated that many of the R-3 waveforms tended toward the truncated or hybrid exponential shapes suggested by Johnson (reference 14) while RPR waveforms were generally trapezoidal.

Predictive equations for $\dot{\mathrm{V}}_\mathrm{I}$ took the form:

$$\text{(0.7)} \qquad \dot{V}_I = \left(0.020222Wt + 0.55332\frac{\dot{V}O_{2\max}}{\overline{HR}}\right)^2 \quad (Day\ 2\ data)$$

for pooled P-1 and P-2 data where Wt = subject weight in pounds, and

$$\text{(0.8)} \quad \dot{V}_I = 2.13882Wt - 0.014196(Wt \times \overline{HR}) + 0.004523(\overline{HR})^2 \quad (Day\ 3\ data)$$

for pooled RPR and FE data (figure 14). No significant difference between actual and predicted $\dot{\mathrm{V}}_\mathrm{I}$ was observed for either Day 2 or 3. Mean PIF were predicted from:

$$(0.9)\quad \overline{PIF} = \sqrt{\begin{array}{c} 48.47145Wt - 138.791HR + 219.9431\dfrac{\dot{V}O_{2\max}}{\overline{HR}} \\ + .51756Wt\overline{HR} - 329.096PIFR \end{array}} \quad \textit{(Day 2 data)}$$

$$(0.10)\ \overline{PIF} = \sqrt{6337.286FVC + 305.0421Wt - 215.2652\overline{HR}} \quad (Day\ 3\ data)$$

No significant difference between actual and predicted $\overline{\text{PIF}}$ was observed for either Day 2 or 3. $\text{PIF}_{\text{max}}$ was estimated from

$$(0.11)\qquad PIF_{\max} = \frac{1}{0.0000605\overline{\overline{HR}}} \quad (Day\ 2\ data)$$

$$(0.12)\qquad PIF_{\max} = 1.087804Wt + 17.6108FVC \quad (Day\ 3\ data)$$

No significant difference between actual and predicted $\text{PIF}_{\text{max}}$ was observed for either Day 2 or Day 3.

Table 6: Respiratory timing responses to light-to-moderate exertion while participating in DECON and RECON tasks on Day 2.

| Task | Variable | Units | R-2 | | | P1 | | | P2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Std. Dev. | Max | Mean | Std. Dev. | Max | Mean | Std. Dev. | Max |
| DECON | $T_i$ | sec | 1.41 | 0.23 | 1.81 | 1.42 | 0.23 | 1.82 | 1.38 | 0.24 | 1.81 |
| DECON | $T_{total}$ | sec | 3.42 | 0.68 | 5.45 | 2.64 | 0.48 | 3.82 | 2.80 | 0.88 | 5.45 |
| DECON | DC | | 0.43 | 0.06 | 0.57 | 0.57 | 0.07 | 0.70 | 0.57 | 0.10 | 0.74 |
| DECON | $T_i/T_e$ | | 0.90 | 0.27 | 1.66 | 2.03 | 0.90 | 4.50 | 2.21 | 1.30 | 5.49 |
| | | | | | | | | | | | |
| RECON | $T_i$ | sec | 1.36 | 0.11 | 1.54 | 1.34 | 0.09 | 1.50 | 1.32 | 0.09 | 1.48 |
| RECON | $T_{total}$ | sec | 3.27 | 0.56 | 4.56 | 2.63 | 0.23 | 2.89 | 2.54 | 0.25 | 2.82 |
| RECON | DC | | 0.44 | 0.06 | 0.56 | 0.54 | 0.05 | 0.66 | 0.56 | 0.05 | 0.66 |
| RECON | $T_i/T_e$ | | 1.02 | 0.29 | 1.58 | 1.54 | 0.44 | 2.64 | 1.80 | 0.64 | 3.00 |

Table 7: Respiratory timing responses to heavy exertion while participating in a firefighter agility test on Day 3.

| Variable | Units | Rest | | | RPR | | | FE | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std. Dev. | Max | Mean | Std. Dev. | Max | Mean | Std. Dev. | Max |
| $T_i$ | sec | 1.43 | 0.21 | 1.89 | 0.89 | 0.14 | 1.2 | 0.79 | 0.12 | 1.1 |
| $T_{total}$ | sec | 3.29 | 0.91 | 5.97 | 1.54 | 0.25 | 2.0 | 1.42 | 0.28 | 2.1 |
| DC | | 0.47 | 0.08 | 0.61 | 0.59 | 0.04 | 0.7 | 0.58 | 0.05 | 0.7 |
| $T_i/T_e$ | | 1.15 | 0.47 | 2.43 | 1.53 | 0.30 | 2.53 | 1.54 | 0.32 | 2.2 |

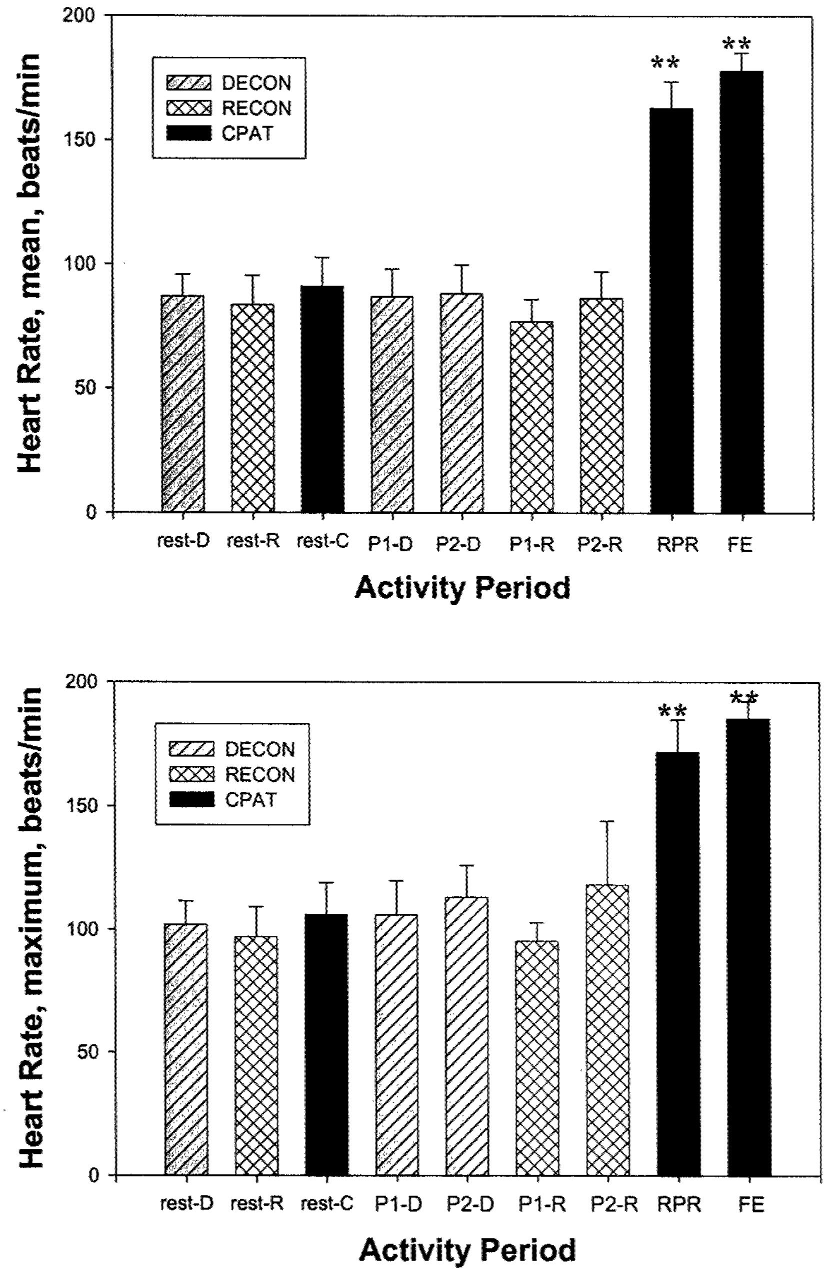



Figure 13: Mean and maximum HR measured during Day 2 and Day 3 events. Activity period 1K = min 5 - 16.7, 2K = min 16.7 – 33.3. Data given as mean ± std. dev. (** - p < 0.01)

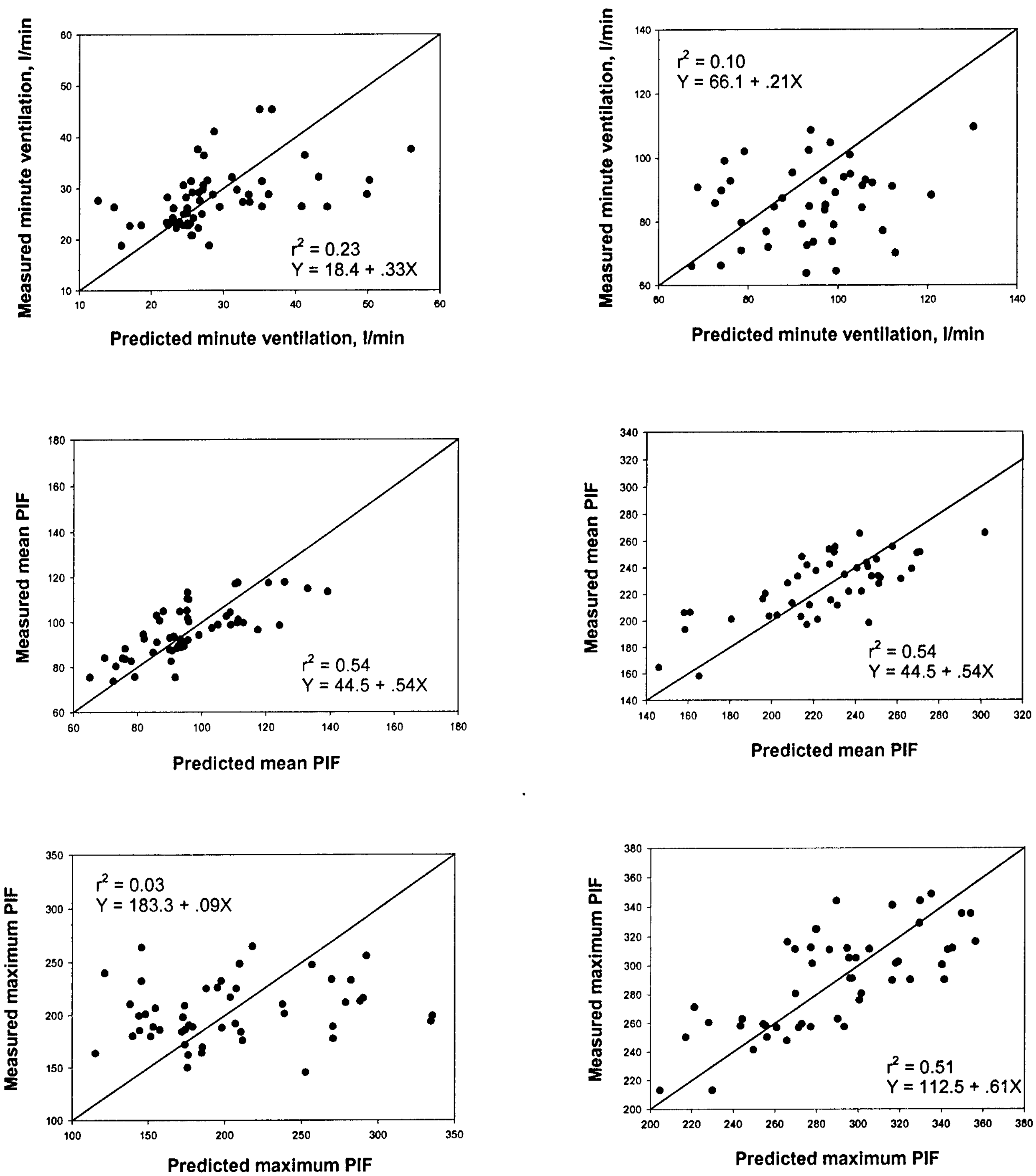



Figure 14: Relationship between predicted and measured $\dot{V}_I$, $\overline{PIF}$, and $PIF_{max}$ for Days 2 and 3. The identity line is included in each figure for reference.

## DISCUSSION

Results from this study suggest that respiratory rates currently used for filter assessment underestimate respiratory demand of individuals performing rigorous physical tasks. Mean $\dot{V}_I$ measured in this study was roughly double that used in current testing. Maximum *individual* mean $\dot{V}_I$ were even higher. These values suggest that filter loading will be much greater than currently tested when performing physically demanding tasks. PIF results suggest that air velocities through filters will also be greater during periods of high exertion. That these peak flows were measured during trapezoidal-type flow profiles suggests that peak or near peak flow rates and velocities will extend beyond a momentary spike. If filter testing is to predict filter performance under operational conditions, then test criteria needs to be revised to better reflect physiological requirements in the field.

These results, while considerably higher than current flow rates used to test filters, are generally consistent with existing literature on respiratory demand during both light-to-moderate and heavy exercise. Very little data exists for respiratory flow rates during *actual* occupational performance but data from laboratory studies conform to the values obtained in the present study. Mean $\dot{V}_I$ during P-1 and P-2 is comparable to data from subjects briskly walking on a treadmill (reference 8) but somewhat less than observed among individuals wearing full-face respirators when walking on an outdoor track (reference 6). Similarly, Louhevaara, et al. (reference 19) observed $\dot{V}_E$ = 40 lpm among individuals wearing an APR while walking on a treadmill at 40% $\dot{V}O_{2max}$. Among the few available occupational studies including respirators, James, et al. (reference 12) observed similar $\dot{V}_E$ among individuals performing moderate work (116W) wearing respirators at room (25°C) and high (43.3°C) temperature (38.0 and 41.8 lpm, respectively). In contrast, Hodous, et al. (reference 11) reported considerably lower *f*, $V_t$, and $\dot{V}_I$ among industrial workers performing somewhat stressful occupational tasks (based on HR measures).

Respiratory timing is another approach to comparing studies. P-1 and P-2 $T_I$ is somewhat greater and DC smaller than found by Harber, et al. (references 6, 7, and 9) during imposition of light to moderate workloads when respiratory impedance plethysmography (RIP) was employed. Pneumotachograph use under identical (reference 7) or similar (reference 8) conditions to when RIP was employed by Harber, et al. (references 6, 7, and 9) produced Ti and DC values very comparable to those found in the present study, suggesting that RIP data may be unreliable for assessing respiratory timing in occupational conditions.

Heavy exertion, represented by RPR, produced $\dot{V}_I$ comparable to results from previous laboratory studies conducted with an APR (references 13, 17, and 24). These studies were conducted with subjects performing at 80% $\dot{V}O_{2max}$ or higher, suggesting that RPR metabolic demands were probably at this level. This is supported by the sustained elevated $\overline{HR}$ observed during both RPR and FE. Subjects in the present study also exhibited $\dot{V}O_{2max}$ levels believed to be necessary to sustain such elevated metabolic demands while performing fire fighter tasks

(references 18 and 20). Other studies, employing an APR with less exertion (approximately 60% $\dot{V}O_{2max}$), reduced $\dot{V}_I$ to approximately 60-75 lpm (references 10, 19, and 22). Obtaining a direct measurement of $\dot{V}O_2$ in a future study would be valuable in determining the actual correlation between exertion level and $\dot{V}_I$ in occupational settings.

Other respiratory parameters show a similar pattern of general compatibility. At heavy workloads (136-271W), Silverman, et al. (reference 24) found somewhat lower DC (.51 - .54) but a similar $\overline{PIF}/\dot{V}_I$ ratio (2.4-2.7). The DC observed by Harber, et al. (reference 8) at maximal exertion closely matched present study findings. Lerman, et al. (reference 17), however, found somewhat higher DC (.64) than the present study but their subjects also had much higher $f$ (54 breaths/min) and lower $V_t$ (1.78 L). These differences may be related to individual differences between subjects but may also reflect different tasking imposed on subjects.

The ability to sustain high exertion levels is limited by the ability to consume oxygen on demand. Considerable evidence suggests that increased breathing resistance cause $\dot{V}_I$ and PIF to decrease while Ti and DC increase (references 5, 23, 24, and 25). The inverse is probably also true; reducing breathing resistance allows for greater $\dot{V}_I$, $\overline{PIF}$, and $PIF_{max}$ upon physiological demand. Louhevaara, et al. (reference 18) observed this when subjects demonstrated no significant difference in pulmonary ventilation without any inspiratory resistance or with a self-contained breathing apparatus (SCBA). This probably explains how the present subjects, performing the same tasks under the same conditions, produced higher $\dot{V}_I$, $\overline{PIF}$, and $PIF_{max}$ when using a powered APR (reference 2).

Higher inspiratory flow under equal physiological demand reduces oxygen debt by allowing more oxygen to reach the pulmonary airways. Reducing oxygen debt forestalls the onset of performance-limiting anaerobic metabolism. Increased flow rates can only be achieved, however, by either increasing the physiological capacity to overcome breathing resistance or reducing breathing resistance, particularly in the inspiratory leg (reference 3).

A fixed breathing resistance, i.e., a respirator filter, imposes unequal demands on individuals of various breathing capacities. Smaller individuals may suffer reduced work capacity due to a lesser ability to overcome breathing resistance (reference 25) given smaller lung volumes (reference 4). Louhevaara, et al. (reference 18) found that physical dimensions are important determinants in identifying individuals capable of performing sustained arduous fire fighting tasks. The relationship found in this study between weight, $\dot{V}_I$, and $\overline{PIF}$ in the present study is suggestive of this, despite all subjects ultimately completing the tasks. Unfortunately, the inability to measure oxygen consumption and a relatively homogeneous subject population in terms of height, weight, and gender, precluded any direct assessment with the current data. A future study into this area could have an impact on predicting operational capabilities of individuals using air-purifying respirators (APCs) based on their physical stature and may also suggest better selection tools for assigning personnel to tasks.

Another question left unanswered by this study was the role experience plays in determining respiratory function in an APC. Harber, et al. (reference 7) and Yasukouchi (reference 25) suggest that inexperience or breathing resistance sensitive individuals may have significantly different breathing patterns from individuals experienced in using a respirator. It may be prudent to examine this to project how the current findings would reflect a military or industrial population with less APC experience than CBIRF members.

This study demonstrated that an asymmetric double sigmoidal model provides a better fit to respiratory curves than a sinusoidal at all exertion levels. This seems to run contrary to LaFortuna, et al. (reference 16) who stated that "A rectangular pattern for inspiratory airflow is never obtained in a healthy individual at rest." Yet use of a respirator even during rest perturbed natural breathing patterns so that "basal" conditions were never approached. This breathing perturbation, in combination with relatively high resting flow rates, suggests that "resting" values reported in the literature are probably inappropriate to apply during respirator use at any level of exertion.

Using an asymmetric double sigmoidal model rather than pure trapezoid better represents physiologic breathing because lung expansion during the initial moments of inhalation gradually accelerates inspired air; this momentary slow acceleration rapidly develops into a near step change to peak or near peak flow (de Koning). Likewise, the wave front decelerates as peak flow is achieved. A sustained flow rate is momentarily attained until continued deceleration gradually end inspiration.

One concern regarding sampling rates was the possibility of missing true $PIF_{max}$ due to rapid changes in sinusoidal flow. This appears less likely given the general shape of inspiratory curves (trapezoid-like double sigmoid). The quasi-plateaus observed in this and other studies (references 14, 16, and 24) suggest that the great majority of peak flows were detected.

Overall, the correlation with other studies suggests that the present results reflect actual respiratory demands experienced during physically demanding operational tasks. These results indicate that high minute ventilation rates approximating those seen during maximum exertion are achievable in occupational settings. In addition, peak flow rates can greatly exceed these values by more than 150%. Failing to account for these high flow rates could also lead to unanticipated levels of filter loading, causing increases in filter resistance and possibly leading to mask seal leakage (reference 21), or higher air stream velocities within filter beds, raising the possibility of breakthrough due to insufficient residence time. Furthermore, increased flow rates may exacerbate problems with breathing resistance (reference 15) in a dose-response relationship. This poses a challenge to respirator filter designers to address these higher-than-anticipated flow rates during both the design and testing phases of filter development and operational deployment.

This study will hopefully prove valuable to the broad industrial and military community of respirator users. It represents a first attempt at measuring respiratory demand in military personnel performing operationally relevant tasks. While CPAT tasks are relevant to the CBIRF mission, examining different military and civilian tasks with greater physical demands or longer durations would greatly add to understanding occupational respiratory demand and how to model it in the laboratory.

## CONCLUSIONS

Respiratory flow rates generated while completing physically demanding tasks are considerably higher than flow rates used to assess filter efficacy.

Results generally conform to existing literature regarding respiratory demand for individuals wearing an APR while performing high workloads near $\dot{V}O_{2max}$.

The instrumentation used in this study was effective in acquiring continuous physiological field data under daunting conditions. Despite this, future studies need to account for significant data losses due to instrumentation failure.

This work explored breathing demand while performing short, high exertion tasks but how this compares to longer duration tasks remains unknown.

Marines (especially CBIRF members), soldiers, and certain industrial workers are familiar with using respirators due to frequent training and use. Other military personnel and industrial workers, however, use respirators only intermittently. Consequently, their breathing demands may differ from these findings when required to use respirators in a field environment due to anxiety or inexperience.

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# APPENDIX A
# PHOTOGRAPHS OF PHYSICAL TASKS

Figure A-1: CBIRF participants seated during the 5-min rest period prior to initiating physical tasks. Note the flow transducer on the respiratory filter along with a signal conditioner and data logger located in front upper pockets.

Figure A-2: Simulated DECON tasks performed on volunteer "victims".

Figure A-3: Examples of RECON tasks performed during Day 2. Other RECON tasks included open field and building searches.

Figure A-4: Subject performing CPAT event No. 1 – stair climb - while bearing 22.7 kg of extra weight on their shoulders.

Figure A-5: Subject performing final portion of CPAT event No. 2 – hose drag.

Figure A-6: Subject walking between CPAT events wearing the 22.7 kg vest without additional shoulder weights. Note the flow sensor mounted on the C2A1 canister (arrow).

Figure A-7: Subject performing the two tasks comprising CPAT event No. 3 – equipment carry. Note that the saws being carried were of unequal size and weight.

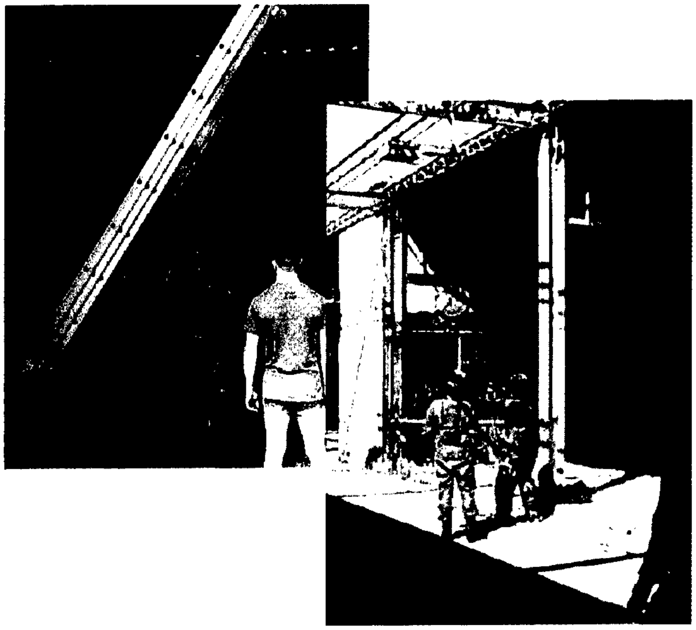

Figure A-8: Subject completing the ladder raise and hose hoist – CPAT event No. 4. The ladder was raised one rung at a time until fully vertical and then lowered in the same manner. The hose was raised up to the ceiling and then lowered.

Figure A-9: Swinging a 10 lb sledgehammer and striking a target (arrow) was the task comprising CPAT event No. 5 (forcible entry).

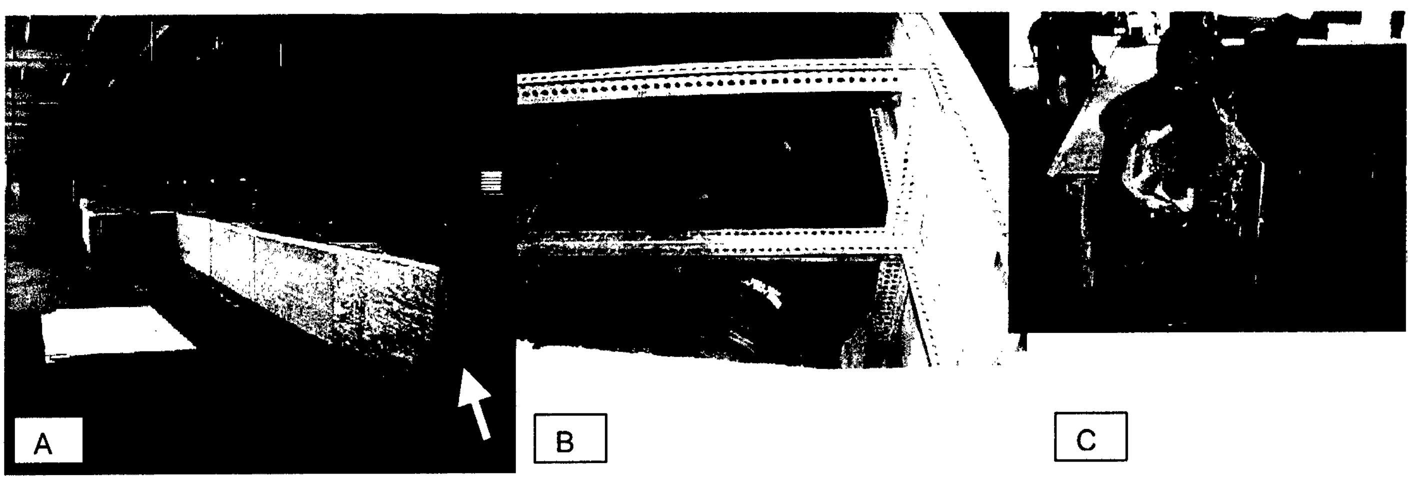


Figure A-10: Outer and inner aspects of CPAT event No. 4 - search. The tunnel used for this event shown in (a) includes a third 90 deg turn indicated by the arrow. Subjects completed this event by crawling through the dark tunnel labyrinth as shown in (b). The top of the tunnel has been temporarily removed to obtain this photograph. The tunnel exit is shown in (c).

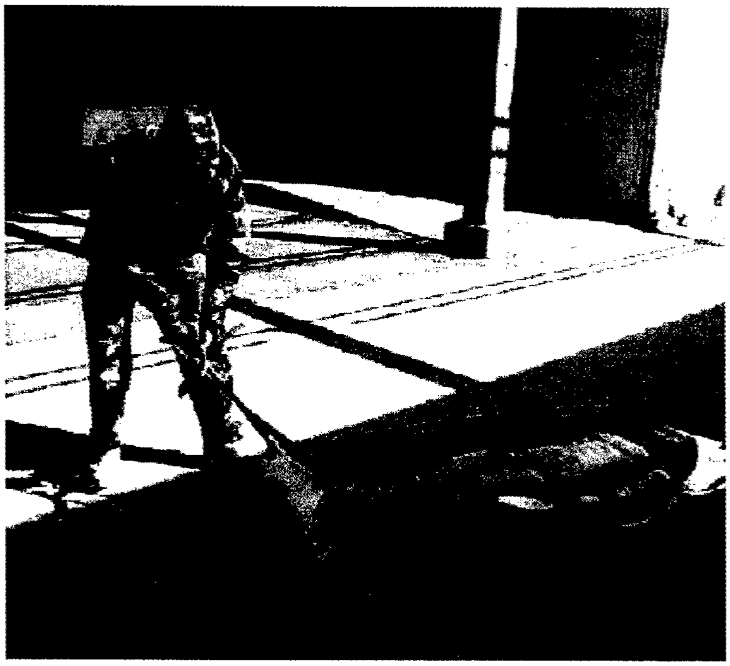

Figure A-11: Weighted dummy dragged around the course delineated for CPAT event No. 7 – rescue.

Figure A-12: Subject lifting the weighted door (arrow) portion of CPAT event No. 8 – ceiling breach and pull. The second arrow points to the other component of this event; the hinged plate which the subject pulls downward.

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# APPENDIX B
# HISTOGRAMS OF BREATHING FREQUENCY, MINUTE VENTILATION, AND MEAN AND MAXIMUM PEAK INSPIRATORY FLOW RATES

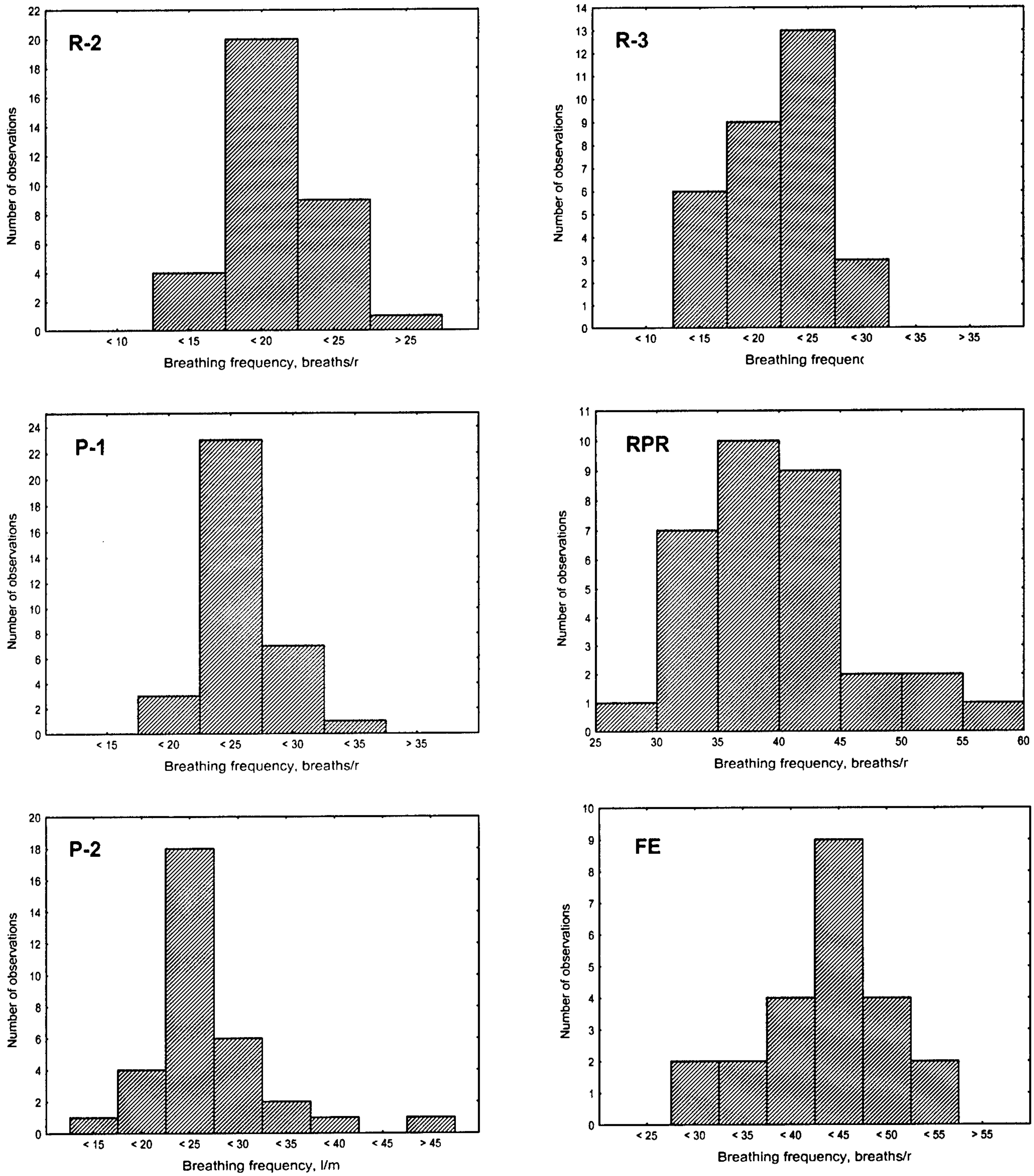



Figure B-1: Range of breathing frequency values observed during Day 2 and 3 trials. The smaller total sample size found in FE results from data loss after 30 min of recording in some trials.

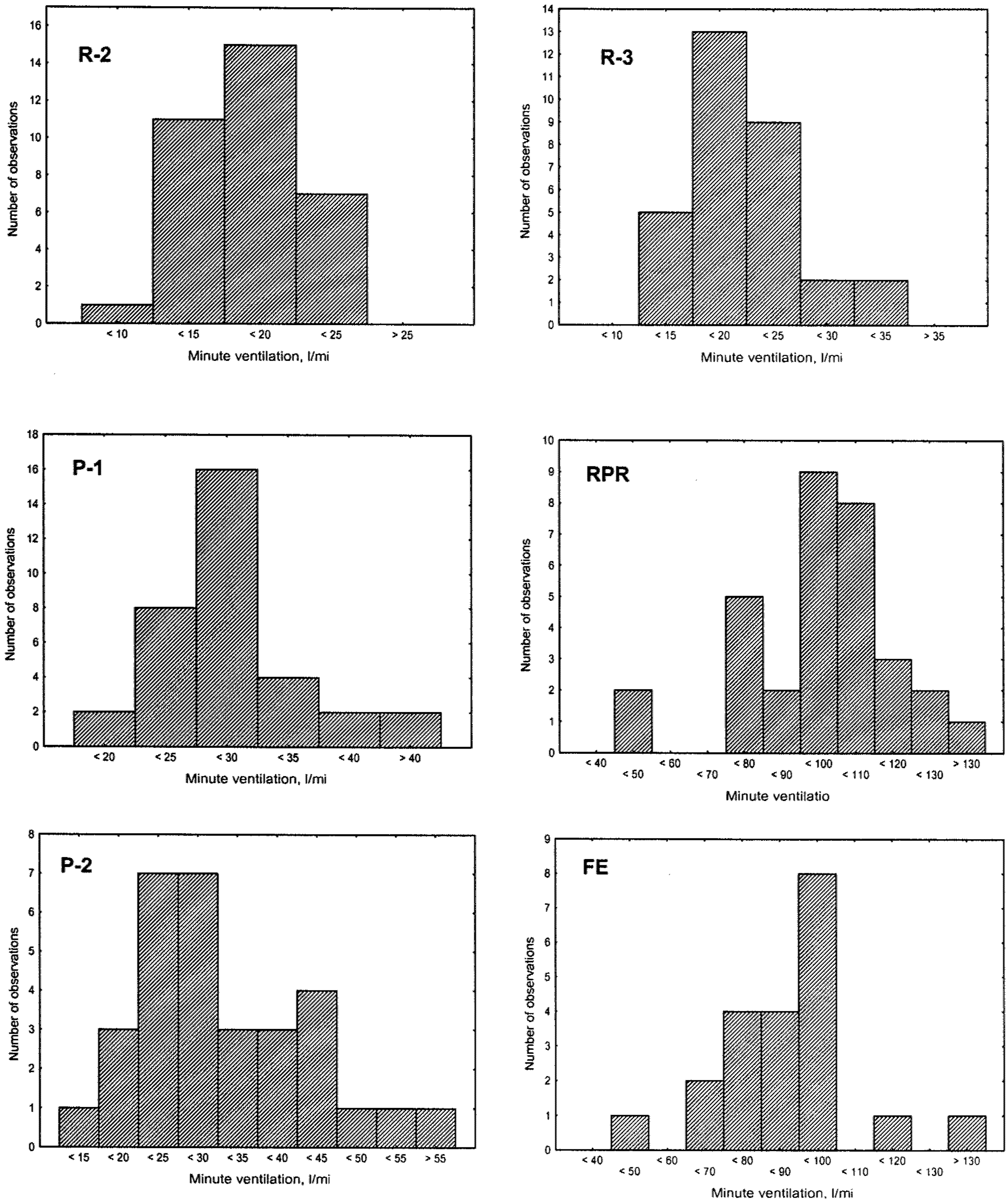



Figure B-2: Range of mean ventilation observed during Day 2 and 3 trials. The smaller total sample size found in FE results from data loss after 30 min of recording in some trials.

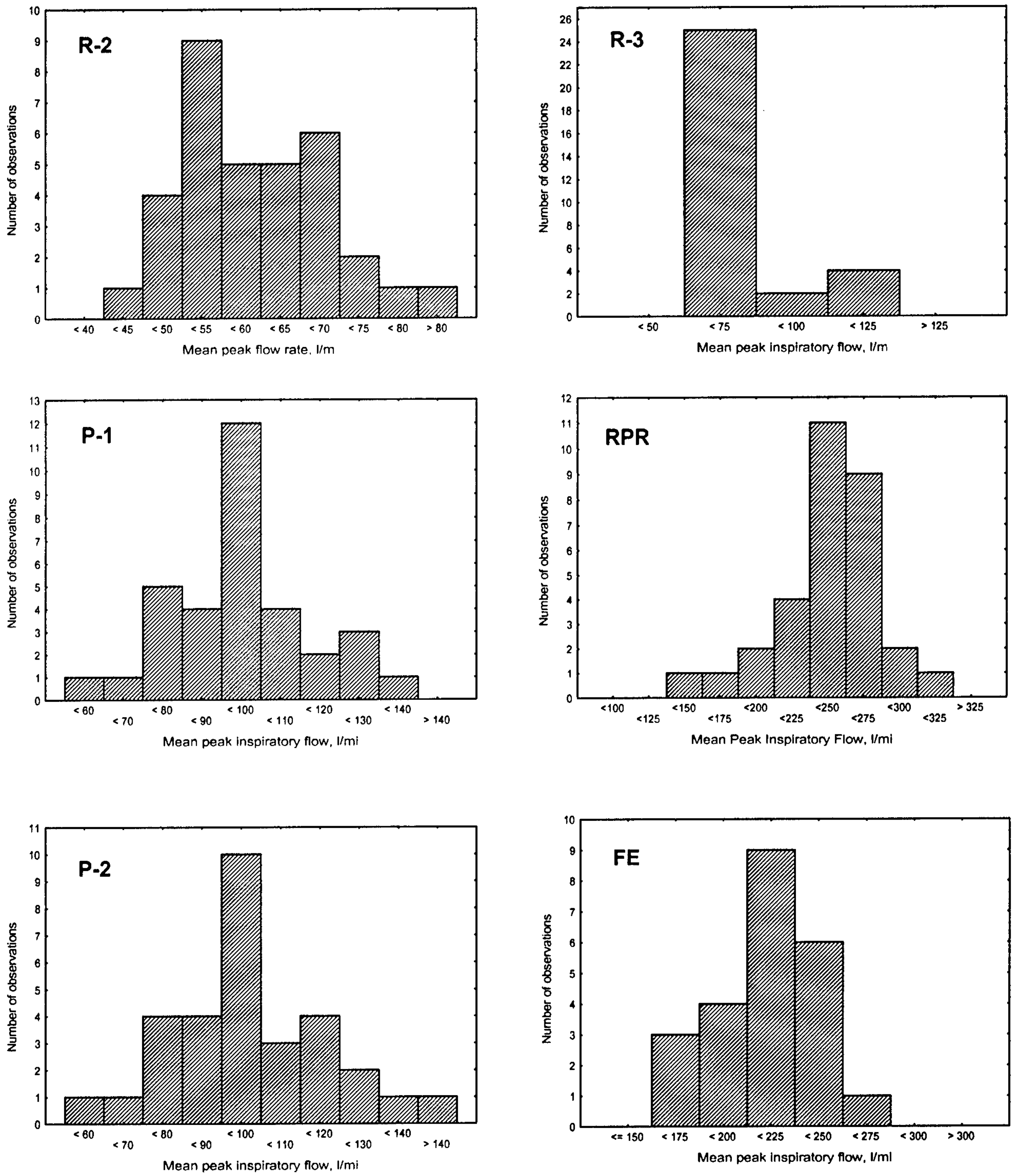
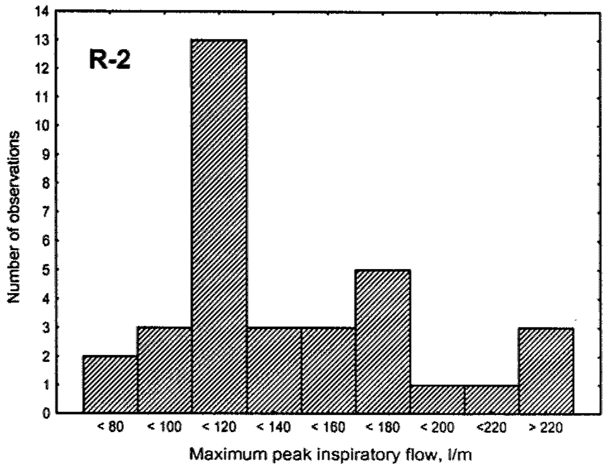
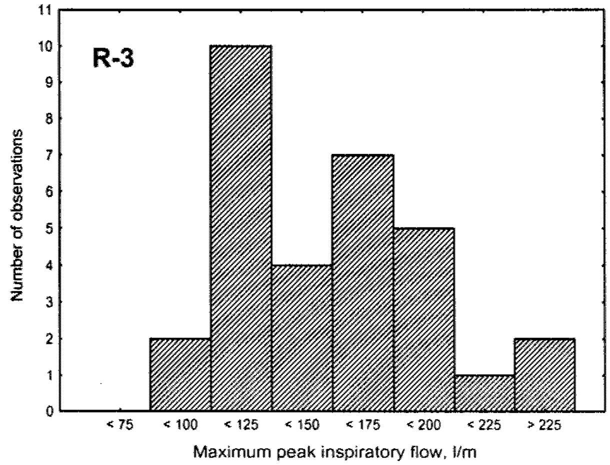
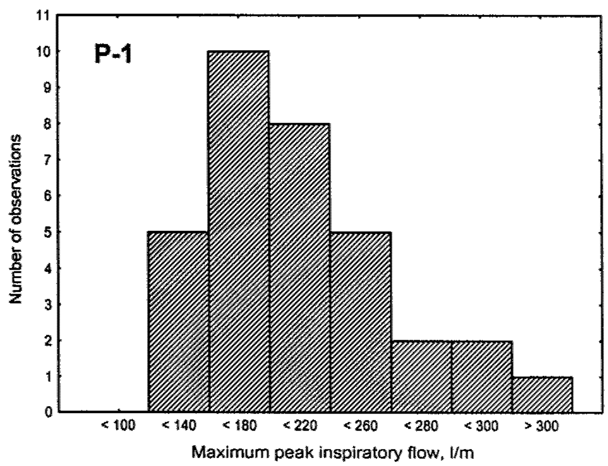
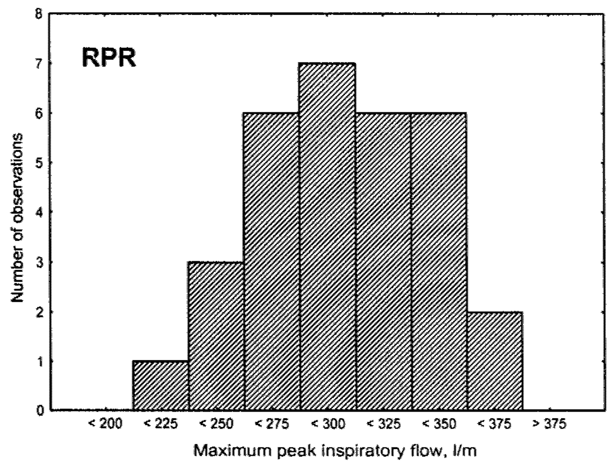


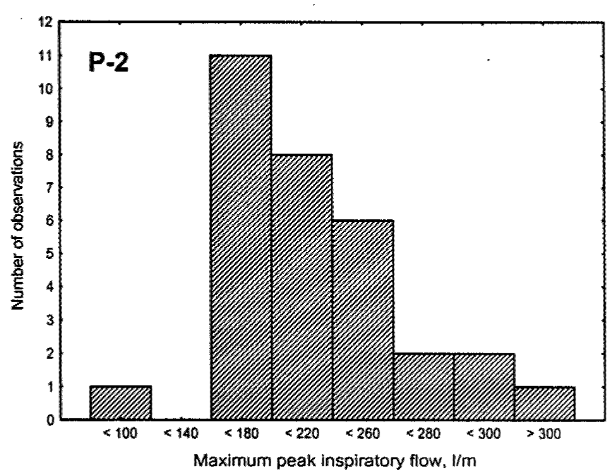

Figure B-3: Range of mean peak inspiratory flow observed during Day 2 and Day 3 trials. The smaller total sample size found in FE results from data loss after 30 min of recording in some trials.



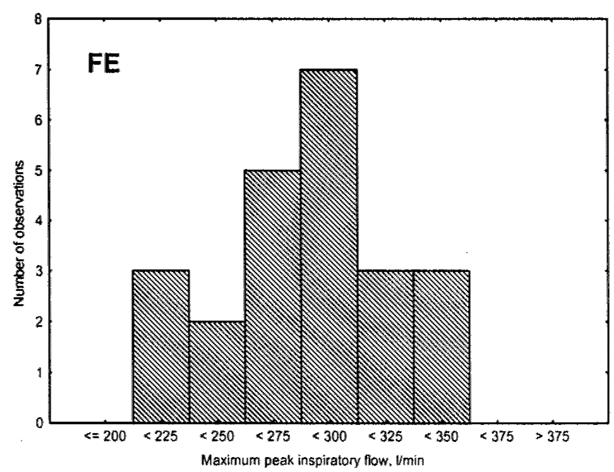




Figure B-4: Range of maximum peak inspiratory flow observed during Day 2 and 3 trials. The smaller total sample size found in FE results from data loss after 30 min of recording in some trials.

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